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Spectral negentropy based sidebands and demodulation analysis for planet bearing fault diagnosis

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ABSTRACT

Planet bearing vibration signals are highly complex due to intricate kinematics (involving both revolution and spinning) and strong multiple modulations (including not only the fault induced amplitude modulation and frequency modulation, but also additional amplitude modulations due to load zone passing, time-varying vibration transfer path, and time-varying angle between the gear pair mesh lines of action and fault impact force vector), leading to difficulty in fault feature extraction. Rolling element bearing fault diagnosis essentially relies on detection of fault induced repetitive impulses carried by resonance vibration, but they are usually contaminated by noise and therefor are hard to be detected. This further adds complexity to planet bearing diagnostics. Spectral negentropy is able to reveal the frequency distribution of repetitive transients, thus providing an approach to identify the optimal frequency band of a filter for separating repetitive impulses. In this paper, we find the informative frequency band (including the center frequency and bandwidth) of bearing fault induced repetitive impulses using the spectral negentropy based infogram. In Fourier spectrum, we identify planet bearing faults according to sideband characteristics around the center frequency. For demodulation analysis, we filter out the sensitive component based on the informative frequency band revealed by the infogram. In amplitude demodulated spectrum (squared envelope spectrum) of the sensitive component, we diagnose planet bearing faults by matching the present peaks with the theoretical fault characteristic frequencies. We further decompose the sensitive component into mono-component intrinsic mode functions (IMFs) to estimate their instantaneous frequencies, and select a sensitive IMF with an instantaneous frequency fluctuating around the center frequency for frequency demodulation analysis. In the frequency demodulated spectrum (Fourier spectrum of instantaneous frequency) of selected IMF, we discern planet bearing fault reasons according to the present peaks. The proposed spectral negentropy infogram based spectrum and demodulation analysis method is illustrated via a numerical simulated signal analysis. Considering the unique load bearing feature of planet bearings, experimental validations under both no-load and loading conditions are done to verify the derived fault symptoms and the proposed method. The localized faults on outer race, rolling element and inner race are successfully diagnosed.

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1. Introduction

Planetary gearboxes are widely used in many sorts of machinery, for example, wind turbines, helicopters, ships and trucks, due to their unique merits such as compact structure, large transmission ratio, strong load capacity, high efficiency and smooth operation. Once fault occurs to planetary gearboxes, it will lead to transmission deficiency, component failure, or even breakdown of the entire drive train. Therefore, planetary gearbox fault diagnosis plays an important role.

A planetary gearbox is mainly composed of gears (including sun, planet and ring), planet carrier, input and output shafts, rolling element bearings and casing. Among these components, gear fault diagnosis has attracted much attention. Research topics range from fault vibration mechanism, fault feature extraction, to fault pattern identification [1,2]. In order to thoroughly understand the vibration mechanism and characteristics of planetary gearboxes, Inalpolat and Kahraman [3,4] investigated the gearbox configuration (such as the number of planets, the planet position phasing and the number of gear teeth) and the gear manufacturing errors on vibration sidebands via dynamics modeling. Mark and Hines [5,6] studied the effects of non-uniform planet loading due to gear imperfections and the modulation effects of planet carrier torque on the sidebands of vibration response. Chaari et al. [7,8] analyzed the effect of gear fault (tooth pitting and crack) on the meshing stiffness, and further analyzed the dynamic response incorporating gear eccentricity and tooth profile error. For condition monitoring and fault detection, Lei et al. [9] proposed two indices, i.e. root mean square of the filtered signal and normalized summation of the difference spectrum, for use under constant running conditions. Bartelmus and Zimroz [10,11] proposed an indicator that reflects the linear dependence between the meshing frequency amplitude and the operating condition, and presented a procedure for load-dependent feature processing, for condition monitoring under nonstationary operations. In order to extract fault signatures from vibration signals, McFadden [12,13] studied the spectral characteristics of planetary gearbox vibration signals, and generalized the time domain averaging method. Samuel and Pines [14,15] proposed a vibration separation method for planet and sun gears, and a constrained adaptive wavelet lifting method to analyze individual tooth mesh waveforms. Barszcza and Randall [16] applied the spectral kurtosis method to detect the ring gear tooth crack in a planetary gearbox. Lei et al. [17] improved the adaptive stochastic resonance method and applied it to extract the weak fault symptoms of a planetary gearbox. Feng et al. [18–20] summarized the spectral characteristics of planetary gearbox vibration signals, presented amplitude and frequency demodulation analysis methods for fault diagnosis under constant operations, and further proposed to extract the time-varying fault signatures under nonstationary conditions via time-frequency analysis. In terms of fault pattern identification, Qu et al. [21] presented a support vector machine based feature selection method to address both binary-class and multiclass classification problems, and applied it to damage degree classification of planet gears. To assess gear fault degree in a planetary gearbox, Zhao et al. [22] proposed to preserve the ordinal information by ordinal ranking, and improved the accuracy of ordinal ranking by a correlation coefficients based feature selection method. Lei et al. [23] adopted multiclass relevance vector machine as a classifier, with the accumulative amplitudes of carrier orders and energy ratio based on difference spectra as indices, to identify health condition of planetary gearboxes. These researches have enriched the literature on planetary gearbox fault diagnosis.

Rolling element bearings also play an important role in planetary gearboxes. To enable efficient power transmission, rolling element bearings are widely used to support the input and output shafts connected to the sun gear and/or the planet carrier, as well as the planet gears. Among these bearings, planet bearings work in a rather harsh loading situation. They need to allow the free rotation of planet gears, and more importantly, they have to bear and transmit the heavy load, in addition to the centrifugal force due to planet gear rotation. Under such harsh working environment, they are more prone to fault. Therefore, planet bearing fault diagnosis is a very important topic for planetary gearbox diagnostics.

Recently, Jain and Hunt [24,25] considered the ring gear deformation and a planet bearing defect, developed a dynamics model of a planetary gearbox, and analyzed the spectral characteristics of vibration response. Bonnardot et al. [26] proposed a signal denoising method based on angle domain resampling, to analyze the vibration signal of a planetary gearbox with a faulty planet bearing. Fan and Li [27] mounted an internal sensor on the planet carrier to avoid the modulation effect due to time-varying vibration transmission path, and proposed a hybrid approach based on cepstrum whitening, minimum entropy deconvolution, SK and squared envelope analysis for planet bearing diagnostics. These works made important contributions to planet bearing fault diagnosis.

However, the reported literature on the topic of planet bearing diagnostics have been very limited so far. This situation is mainly caused by the dynamics complexity of planet bearings. Planet bearing kinematics involves both spinning around the planet pin and revolution with the planet carrier about the sun and ring gear center. Under such a complex motion, the fault characteristic frequencies are completely different from those of fixed-axis bearings.

Meanwhile, planet bearing vibration signals exhibit stronger modulation features and therefore higher complexity than fixed-axis bearings. Sensors are usually fixed to the gearbox casing to measure vibrations. In such cases, in addition to the load zone passing effect, the revolution and spinning lead to extra complex effects on the fault induced vibration, such as the amplitude modulation (AM) due to the time-varying vibration transfer path from the fault point to sensors, and the AMs caused by variation in the angle between the gear pair mesh lines of action and the fault induced impact force vector (in the cases of outer race and rolling element fault). These factors lead to high complexity of planet bearing vibration signals and therefore add difficulty in fault feature extraction.

Moreover, difficulty in properly selecting a signal component sensitive to planet bearing faults is another major reason. Faults in rolling element bearings produce repetitive impulses in vibration signals, and these impulses are mainly carried by resonance. Nevertheless, they are usually of low amplitudes and buried in background noise. Therefore, it is important to find